Columbia Water Center White Paper

America's Water Risk: Water Stress and Climate Variability

February 2013

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Summary

The emerging awareness of the dependence of business on water has resulted in increasing awareness of the concept of "Water Risk" and the diverse ways in which water can pose threats to businesses in certain regions and sectors. Businesses seek to secure sustainable income. To do so, they need to maintain a competitive advantage and brand differentiation. They need secure and stable supply chains. Their exposure risks related to increasing scarcity of water can come in a variety of forms at various points in the supply chain. Given increasing water scarcity and the associated deterioration of the quantity and quality of water sources in many parts of the world, many "tools" have been developed to map water scarcity risk or water risk. Typically, these tools are based on estimates of the average water supply and demand in each unit of analysis. Often, they are associated with river basins, while business is associated with cities or counties. They provide a useful first look at the potential imbalance of supply and demand to businesses.

While industry accounts for only 18% of direct water use, industrial supply chains may have more water risk due to climate variability.

However, the analyses on which such tools are based understate the potential water risk due to climate variations. In most places, even if the resource is not over-appropriated on average, persistent shortage induced by climate conditions can lead to stress. A clear understanding of shortages induced by droughts, in terms of the magnitude, duration and recurrence frequency will better inform the water businesses and water related sectors. To properly diagnose water risk, one needs to examine both existing demand and variations in renewable water supply at an appropriate spatial resolution and unit. A metric that can inform the potential severity of a shortage is the accumulated deficit between demand and supply at a location. ***Here, we provide ways to estimate this risk and map it for the USA at a county level***. The measures of water risk are estimated using over sixty years of precipitation and the current water use pattern for each county. Unlike past work that considers estimates of groundwater recharge and river flow as measures of supply, we use precipitation as the renewable water supply endogenous to the area, and consider natural and human uses of this water. ***The reliance on imported river water or mined ground water is exposed in the process.*** This is important to establish in the face of spatial competition for existing water resources.

Two risk metrics are developed to capture the influence of within year dry periods (Normalized Deficit Index - ***NDI***) and of drought across years (Normalized Deficit Cumulated - ***NDC***)***.*** The NDI is computed as one number for each year using *historical* daily rainfall data for the area and *current* daily water needs. It measures the maximum cumulated water shortage each year during the dry period that needs to be provided for from ground water or from surface water storage or transfers from other areas. The NDC is computed as one number over the historical climate record. It represents the largest cumulative deficit between renewable supply and water use over the entire period. Consequently, it reflects the stress associated with multi-year and within-year drought impacts at a location. Given that 60 years of historical climate data were used, the maximum of the NDI (i.e. the worst single year), and the NDC (i.e., the effect of a string of bad years) may have an average recurrence interval of approximately 60 years. The NDI data provides insights into other recurrence intervals as well. Through a comparison of NDI and NDC, we observed that the agricultural belt of the Mid-West is prone to multiyear drought risk and the resulting shortages will exceed the average renewable endogenous supply in the region.

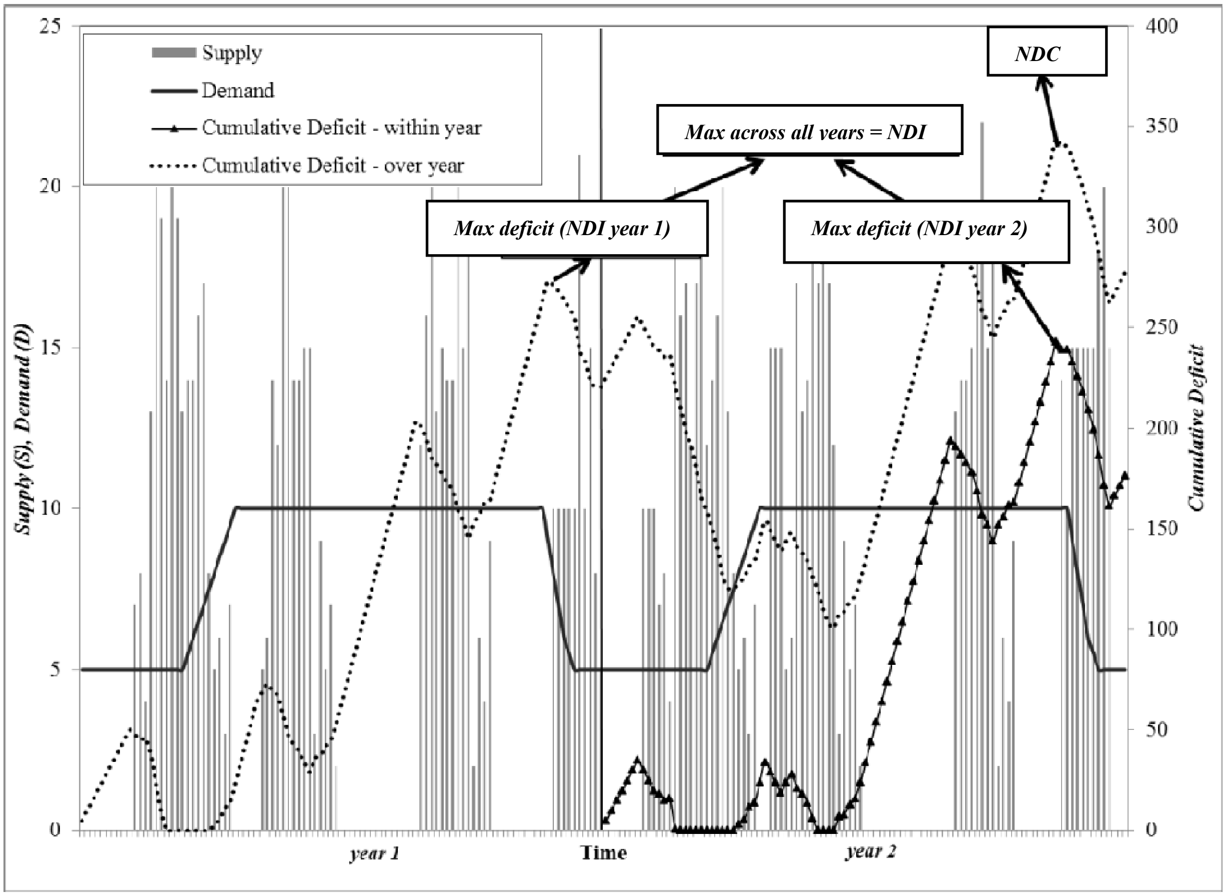

Figure 1: Conceptual representation of the Stress Indices *NDI* and *NDC.* The figure shows a stochastic realization of the supply and demand over time for two years. The potential stress in each year is the maximum annual cumulative deficit for that year. Two cumulative deficit curves are shown. The first one (dots) plots the continuous cumulative deficit for the two years. The second curve (connected dots) shows the cumulative deficit for year 2, after a reset to 0 at the beginning of year 2. *NDI* is the maximum of the cumulative deficit computed for year 1 and the one computed after reset for year 2. The maximum multiyear cumulative deficit (*NDC*) is obtained as the maximum of the continuous cumulative deficit curve (dots) over the two years. **(Figure adopted from *Devineni et.al (2012)*)**

Approach

The ***Water Risk Indices*** developed here are based on the sequent peak algorithm originally developed for reservoirs. It quantifies the water storage capacity needed to meet the demand for a given sequence of supply (Lall and Miller 1988; Loucks et al. 1981; Thomas and Burden 1963). The daily water deficit is defined as the difference between the daily water demand and the daily renewable water supply. The deficits are accumulated while setting negative accumulations to zero. The maximum accumulated deficit in a given year divided by the average annual rainfall across the historical period is the NDI for that year. Similarly the NDC is the maximum accumulated deficit for all years divided by the average annual rainfall. The process is illustrated in Figure 1. The *NDI is* estimated separately for each of the 2 years considering the within-year rainfall pattern in each year. The *NDC* is estimated as the worst across both years. With 60 years of data, the 6th largest NDI value indicates that there is an approximately 10% chance that water storage or transfers of that amount may be needed to meet demands at that location in any given year if multi-year droughts were not considered. The NDC indicates the worst case in 60 years. A detailed description of the mathematical model along with applications and interpretation can be found in *Devineni et.al (2012)*.

The results for the USA

To provide context, it is instructive to review the patterns of annual rainfall across the USA. The average annual precipitation and its Coefficient of variation (standard deviation divide by mean) are shown in Figure 2. The coastal regions and the North East appear to be well endowed with precipitation, while the Southwest and parts of the Midwest are marked by high variability in precipitation across years. The interior West is dry. The risk indices described above are computed for each of the 3111 counties in the continental USA using 61 years of daily climate records and the most recent national statistics that inform the current water use attributes for Agriculture, Industrial, Mining, Aquaculture, Livestock, Domestic and Thermoelectric water withdrawals. Much of the water use in many counties is related to agriculture. The spatial pattern associated with cropped area is shown in Figure 3, and the total estimated annual water demand by county is presented in Figure 4.

It is important to realize at this juncture that while water supply entails physical and institutional settings with defined water rights in some regions, incorporating such appropriations and institutional factors is a challenge given the lack of a comprehensive data source for such non-physical factors. Moreover, contrary to most applications of water risk indices, for our application, we are considering the supply to be defined by the rainfall over the accounting unit (i.e. the county). We did not consider additional sources such as canals or rivers coming into or leaving the county since constraining the hydrologic approach at daily scale and a fine scale accounting unit is a challenge. For instance, if one took account of all stores and fluxes to assess stress, one would need to consider also the fluxes in and out of the deep groundwater, shallow groundwater and natural and manmade reservoirs, and estimating these reliably is a challenge. Moreover, while water balance terms define actual water stress, this would be conditional on allocation or operation rules which are usually not available nationally. Changing the question to “how sustainable are the water resources in this accounting unit, if we consider only the renewable endogenous supply as defined by the rainfall in the unit”, allows for a more direct assessment. This takes away the endowment issues and implicitly reveals dependence on exogenous supplies. A thorough discussion on the choice of accounting unit is presented in *Devineni et al. (2012)*.

Gridded daily rainfall and temperature data from 1949 – 2009 (61 years) available at $1/8^0$ by $1/8^0$ spatial resolution (Maurer et al. 2002) were interpolated to each of the 3111 counties in the continental USA. For computing the agricultural water demands, the most recent data on harvested crops and the total cropland for each county were extracted from the National Agricultural Statistics Services (NASS, http://www.nass.usda.gov/). The daily crop water requirements are estimated based on FAO recommended crops coefficients and reference crop evapotranspiration (Hargreaves and Samani, 1982). Estimates on the county level industrial, livestock, mining, aquaculture, thermoelectric and domestic water withdrawals were obtained from United States Geological Survey (USGS) water use database (http://water.usgs.gov/watuse/). The renewable water supply is estimated as a fraction (70%) of daily rainfall available over the cropland and a smaller fraction (10-15%) of rainfall available from the non-cropped area in the county. This conceptually resembles the process one can model for bare soil evaporation, soil moisture dynamics and runoff generation.

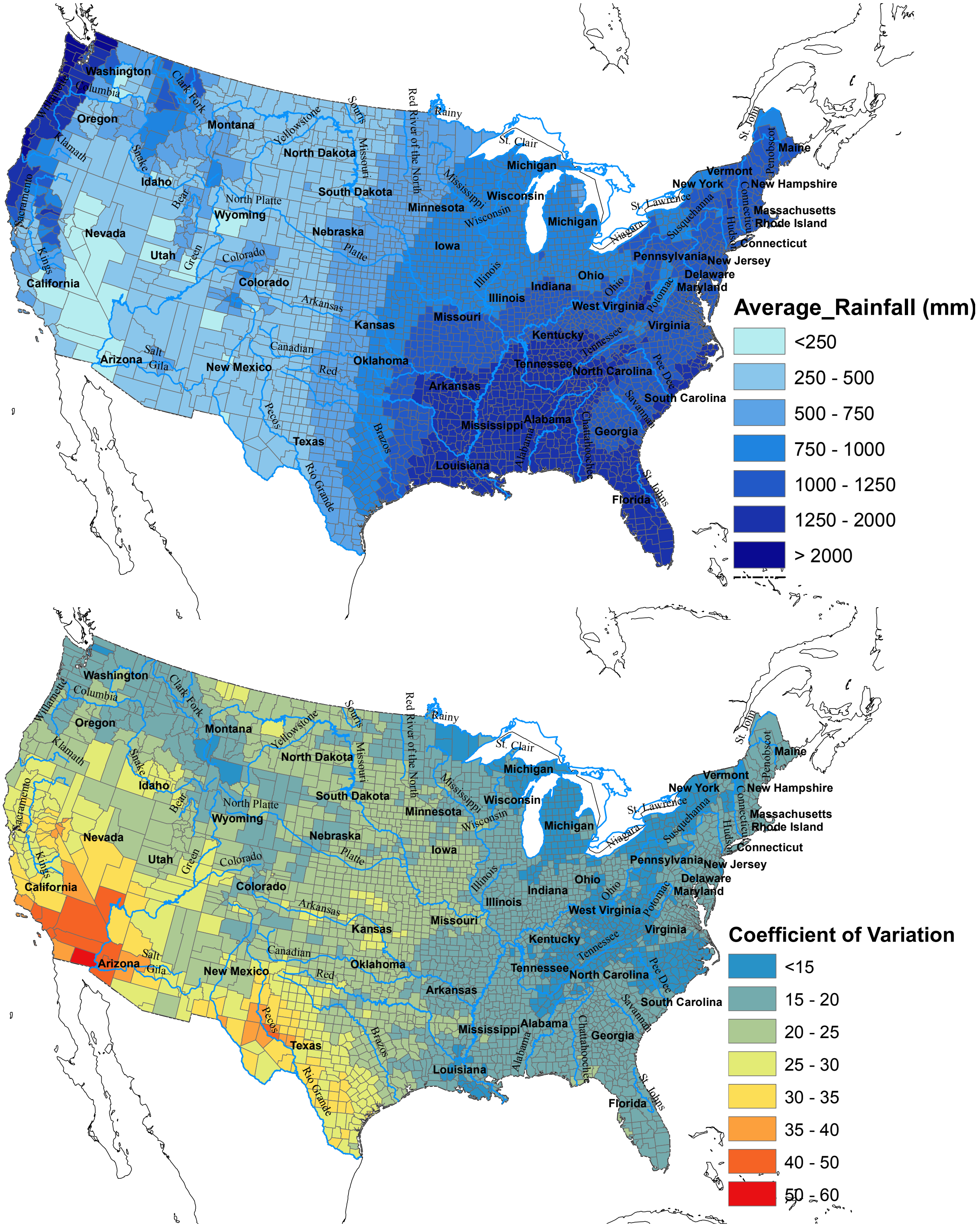

Figure 2: Mean annual precipitation in mm/year and the associated coefficient of variation as % deviation from the mean.

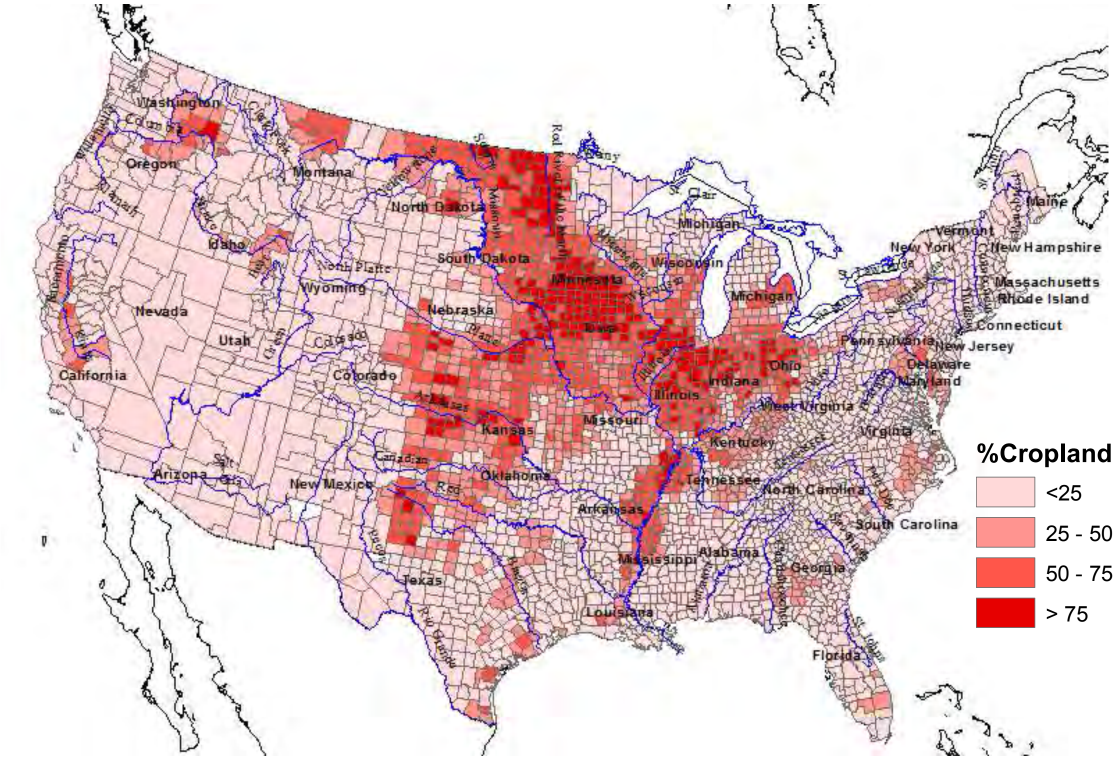

Figure 3: Current US Cropping pattern as net cropped area/county area.

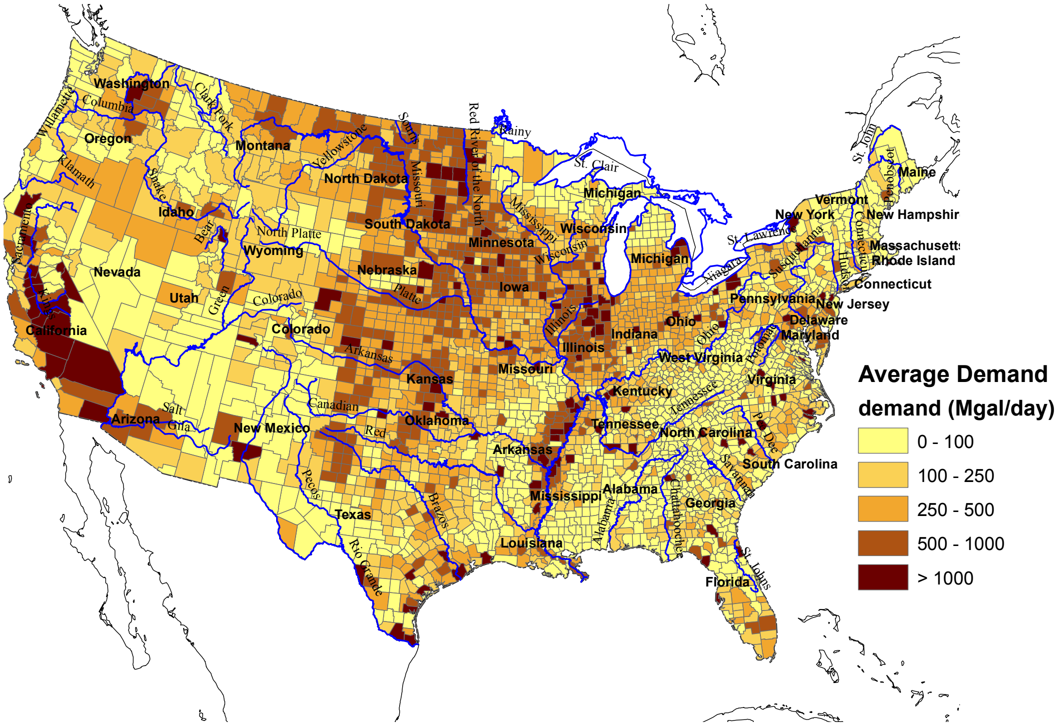

Figure 4: Average annual water demand for the USA.

NDI and NDC comparison

The Normalized Deficit Index (NDI) and the Normalized Deficit Cumulated (NDC) as shown in Figure 5 provides insights on how much out of kilter the conditions are with respect to its local climatology, i.e. the average rainfall in the county. Hence, NDI or NDC less than 1 indicates that the magnitude of cumulative deficit or risk is less than the average annual rainfall. Similarly, NDI or NDC greater than 1 represents the case where the external dependence (or storage) or shortage during a run of bad years is greater than the average rain locally. The annual rate of consumption in these regions could also be higher than the average utilizable rainfall rates. From Figure 5 we see that for the year with the worst deficit (this has a chance of happening once in 60 years), most of the country has $NDI < 1$ indicating moderate storage requirements or water stress. As one considers persistence in climate beyond 1 year, we see from the NDC map that the current use patterns portend severe stress over much of the agricultural belt of the mid west USA as well as the arid regions of California and Arizona. Chronic or multi-year stress consequently emerges as the event of concern in these areas with many locations requiring greater than 2 times to greater than 5 times the average annual rainfall in the location in storage or to be transferred from other locations to make it. Again, this has a chance of happening at least once in 60 years on average.

An investigation into the causal mechanisms of these droughts will provide the ability to develop prognostic climate information based forecasts of the risk up to 6 months ahead that can serve as a means to manage a water utility, regional water allocation or a company's business operations.

With further investigation of NDI and NDC for each county we developed a map that describes the regions susceptible to persistent drought resulting from natural variations in climate and existing demand. The spatial distribution of water stress for USA is illustrated in Figure 6. The counties shown in blue have NDC equal to the maximum NDI achieved in any given year, i.e., multi-year droughts do not have an impact worse than that of the driest year on record. This could either be due to the absence of long droughts or due to a relative level of demand that is low enough to not require storage across years. The counties marked in orange have NDC greater than the max NDI, and for the ones marked in red the NDC is more than ten times the max NDI, indicating that multi-year drought impacts can be particularly severe. In these cases demand reduction may be particularly beneficial unless a high amount of storage or diversion is available. The red case reflects demands that exceed total endogenous supply and reflect locations where desalination or groundwater mining or imported water is necessary to meet existing demands.

The map of NDC can help identify regions with significant multi-year climate induced water stress. A probabilistic risk analysis of the magnitude of the cumulated shortage can be provided for each location. Here, a 1 in 60 year recurrence is illustrated. These risks can be mapped to potential climate risks for water supply operations, agriculture and supply chains, specific to each business.

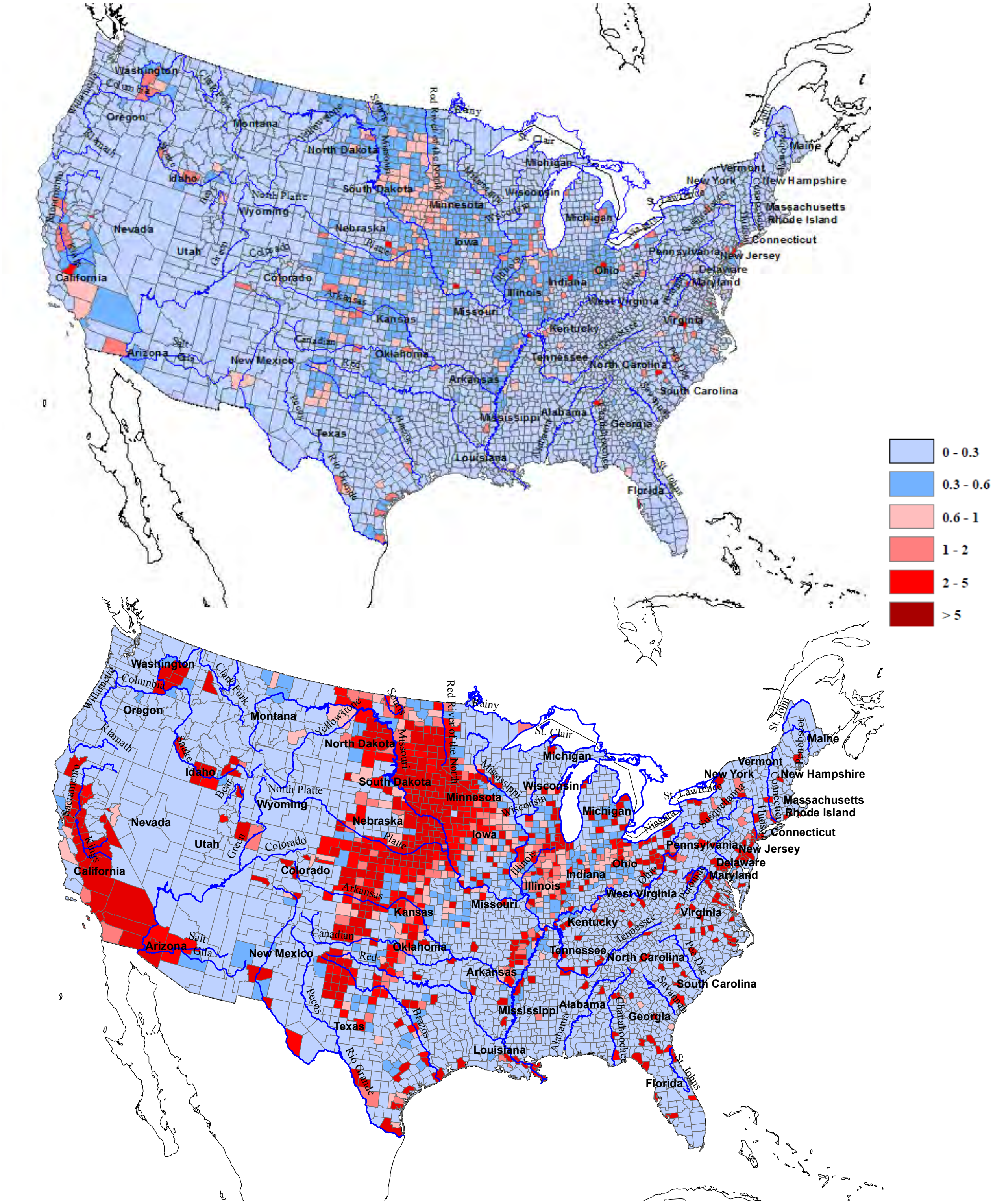

Figure 5: Magnitude of water stress across the continental USA under within year (NDI, top panel) and multiyear cumulative analysis (NDC, bottom panel) for 1949-2009 daily supply and demand data.

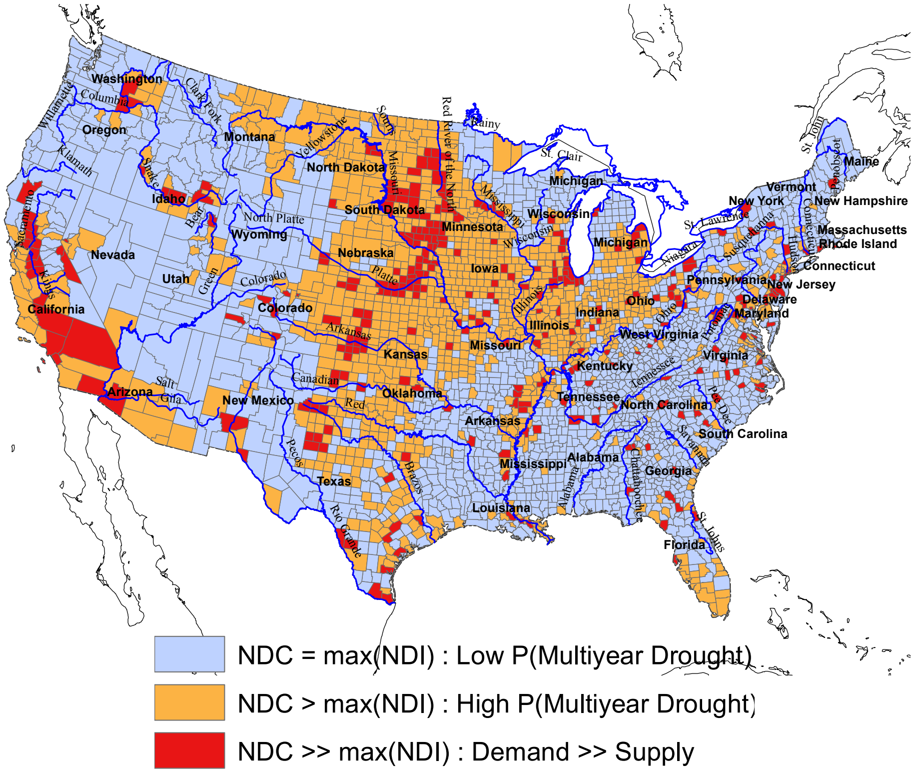

Figure 6: Spatial categorization of the magnitude and distribution of water deficits and drought risks in USA. Blue: Multi-year Stress = Worst single year stress. Brown: Multi-year stress is higher. Red: Demand exceeds average annual endogenous supply in the county.

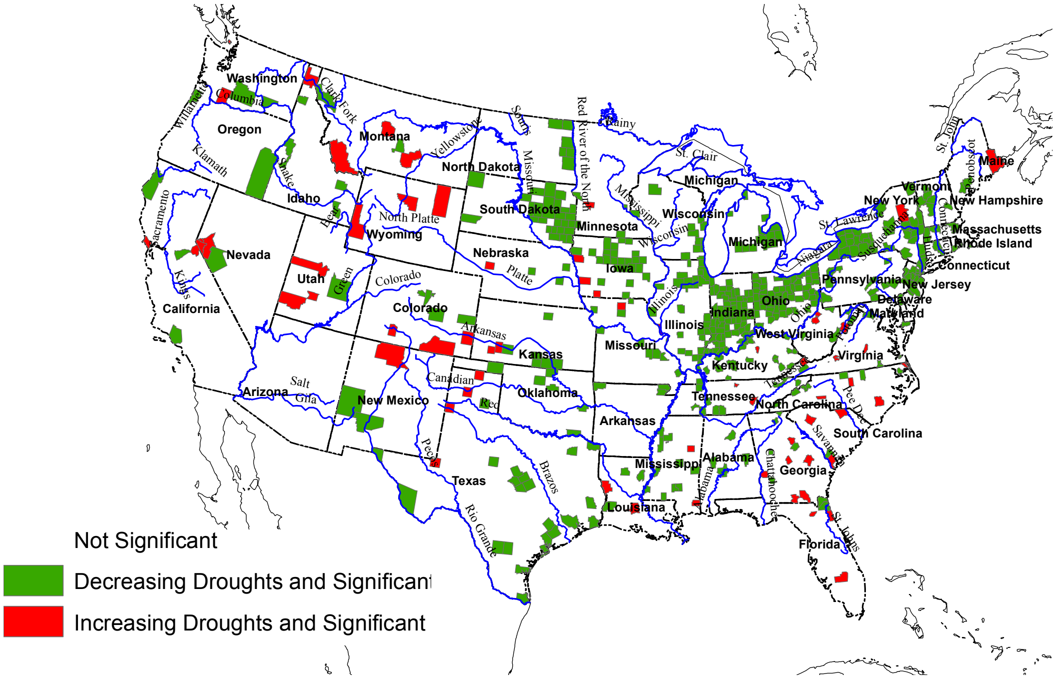

Figure 7: Time Trends in Water Stress (Significance level =95%)

Trends in Water Stress

Based on the 61 year (1949 - 2009) time series of NDI estimates we assessed the monotonic trends in the incidence of drought events using the Mann-Kendall non-parametric trend test (Mann 1954; Helsel and Hirsch, 1992). The Mann-Kendall test is a rank based test that is used for detecting trends in extremes with no assumption of the underlying distribution of the data. Figure 7 shows the results from the test for each county. The counties colored red indicate that the NDI have an increasing trend that is statistically significant at the 95% confidence level. Similarly, the counties colored green have a decreasing trend in NDI that is statistically significant at the 95% confidence level. The rest of the counties in white color have no statistically significant trends. The only large contiguous areas with decreasing trends in NDI, which reflect reduced persistence in dry days, are in the Midwestern United States. Scattered locations in the West exhibit increasing trends.

Summary

- The ***water risk indices presented*** focus on stress as defined through a temporal integration of deficit at a daily resolution, rather than using annual averages, and hence can be examined at different levels of aggregation, e.g., seasonal, annual or over the period of record. The average supply demand imbalance is automatically accounted for.

- The index directly informs storage requirements needed to meet the projected supply-demand imbalance at desired levels of reliability (explicit or implicit), and hence can be connected more directly to infrastructure, planning or water conservation needs, or the size of trans-basin diversions.

- For climate informed analyses of water risk, the index emphasizes that the climate information needs to properly represent the time sequence of supply and demand, and not just average seasonal or annual values, to be of value for decision making.

- The within year and multi-year examination of potential risk makes it easy to understand the potential exposure magnitude and duration by location, and is hence useful for siting decisions.

- Future Climate Scenarios or Season ahead climate forecasts can be readily accommodated to provide projected risk, and integrated with a stress monitoring plan that indicates the current level of accumulated deficit or stress.

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